Exploring CEνNS of reactor neutrinos with the NUCLEUS experiment

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Abstract. Coherent elastic neutrino-nucleus scattering (CEνNS) offers a unique way to study neutrino properties and to search for new physics beyond the Standard Model. The NUCLEUS experiment aims to measure CEνNS of reactor anti-neutrinos down to unprecedented low nuclear recoil energies. The novel gram-scale cryogenic detectors feature an ultra-low energy threshold of $\leq$20 eV$_{\mathrm{nr}}$ and a rise time of a few 100 μs which allows the operation above ground. The fiducialization of the detectors provides an effective discrimination of ambient γ- and surface backgrounds. Furthermore, the use of multiple targets promises a high physics potential. The NUCLEUS experiment will be located at a new experimental site at the Chooz nuclear power plant in France, providing a high anti-neutrino flux of $1.7 \cdot 10^{12}\ \bar{\nu}_e/(\mathrm{s} \cdot \mathrm{cm}^2)$. The commissioning of the experimental setup with a comprehensive background measurement is planned for 2022.

1. CEνNS of reactor anti-neutrinos

Coherent elastic neutrino-nucleus scattering (CEνNS) is a well predicted Standard Model (SM) process [1], and can be used to probe its validity as well as to search for new physics. The first observation of CEνNS has been reported in 2017 by the COHERENT collaboration using a 14.6 kg CsI[Na] scintillation crystal deployed at the Spallation Neutron Source (SNS) at the Oak Ridge National Lab [2]. The stopped pion decay at rest (DAR) source at the SNS provides a pulsed neutrino beam with a flux of $4.3 \cdot 10^7$ neutrinos/(s·cm^2) at 20 m from the source and a neutrino spectrum reaching up to 53 MeV. In a second measurement with a much lighter target, argon, the COHERENT experiment could confirm the N^2-dependence of the CEνNS cross-section on the neutron-number of the target [3].

With a neutrino flux of $\mathcal{O}(10^{20})\,\bar{\nu}_e$/s per $\mathrm{GW_{th}}$, nuclear reactors are a promising neutrino source to study CEνNS at even lower energies than DAR sources. Electron anti-neutrinos are produced in the beta-decays of the fission products of the nuclear fuel with energies reaching up to 10 MeV. Thus, reactor $\bar{\nu}_e$ are expected to be in the fully coherent regime of the elastic neutrino-nucleus scattering.

Due to the full coherence and the extremely low momentum exchange in CEνNS of reactor neutrinos, this process is particularly interesting for a precision measurement of the neutral weak current. Such a measurements allows to determine the Weinberg angle at low momentum transfer. On the other hand, deviations from the SM predictions may reveal new physics, such as additional neutrino-quark couplings [4].

Although, several different experiments deployed at nuclear reactors are planned or ongoing, an observation of CEνNS of reactor anti-neutrinos is still missing [5, 6, 7]. A key challenge to measure CEνNS of $\bar{\nu}_e$ of a few MeV, is the necessary low energy threshold to detect the sub-keV nuclear recoils induced by the scattering. Furthermore, experiments in the proximity of a nuclear reactor, are typically located at shallow overburden. Being at a few meters of water equivalent (m.w.e.), active and passive shielding techniques need to be applied in order to reach a background level well below the expected CEνNS rate. The requirements of a low background and a sub-keV energy threshold are the same as for light dark matter searches naturally leading to a large synergy of the two fields. The NUCLEUS experiment tackles both challenges, i.e. a low energy threshold of $\mathcal{O}(10\,\mathrm{eV})$ and an envisioned background count rate of 100 counts/(keV·kg·days), by deploying gram-scale cryogenic calorimeters [8]. The detector concept is based on the technology developed in the framework of the CRESST experiment, which is a leading experiment in the field of direct low mass Dark Matter search [9].

2. The NUCLEUS detector concept

The NUCLEUS experiment aims to study CEνNS of reactor anti-neutrinos using gram-scale cryogenic calorimeters read out with W-TES [10]. The target detectors, $(5\,\mathrm{mm})^3$ $CaWO_4$ and Al_2O_3 crystals, enable ultra-low energy thresholds in the few eV range. A prototype Al_2O_3 detector with a mass of 0.5 g reached an energy threshold of $\mathrm{E_{th}} = (19.7 \pm 0.9)\,\mathrm{eV_{nr}}$ [11]. Furthermore, the small size of the crystals implies a total event rate per crystal of $\leq 1\,\mathrm{Hz}$ and, thus, ensures an operation above ground with a negligible dead time of $\mathcal{O}(1\%)$.

The target detectors will be arranged in a 3×3 array of $CaWO_4$ crystals with a total mass of 6 g, and a second array consisting of nine Al_2O_3 crystals, with 4 g total mass. With this multi-target approach we exploit the N^2-dependence of the cross-section. While with $CaWO_4$ we expect to measure the CEνNS signal on top of the background, the neutrino scattering rate will be suppressed for Al_2O_3 providing an in-situ background measurement. By constraining the background model based on the Al_2O_3 measurement, we can increase our sensitivity to CEνNS [12].

The target detectors will be embedded within a series of cryogenic detectors serving as a fiducial volume detector for active background rejection, see Figure 1. The support structure

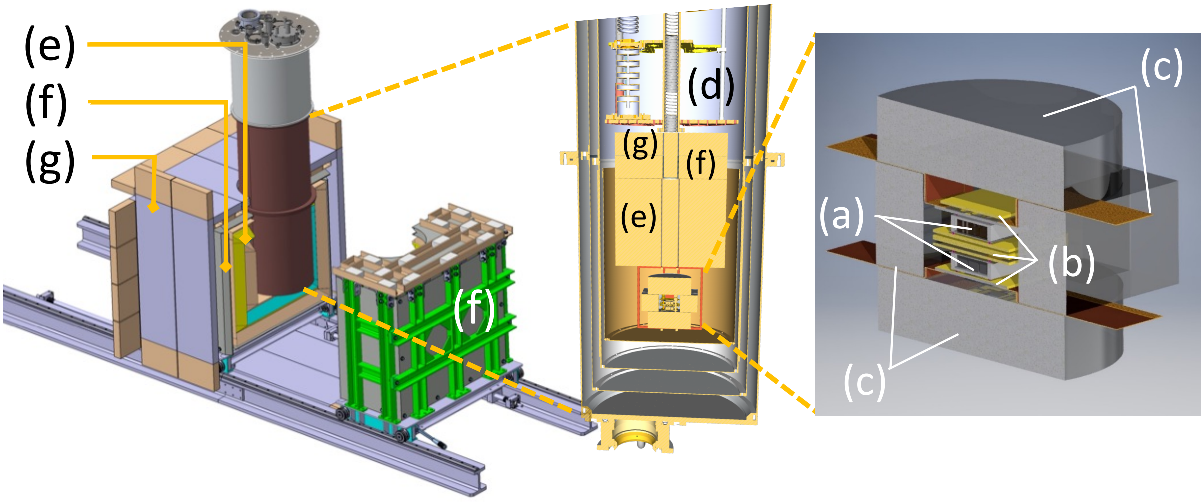

Figure 1. Sketch of the NUCLEUS experiment. **Right**: the target detectors (a) are arranged in two 3×3 arrays with a total mass of 6 g ($CaWO_4$) and 4 g (Al_2O_3) which are mounted inside an instrumented Si holder, the inner veto (b). The inner cryogenic detectors are surrounded by cryogenic Ge detectors (c), the Ge outer veto. **Middle**: The cryogenic detectors are operated inside a dilution refrigerator (d). **Left**: The dilution refrigerator enters the passive shielding consisting of PE (e) and Pb (f). The passive shielding is surrounded by an active muon veto (g). The full shielding is mounted on a movable mechanical structure. Passive and active shielding layers are continued inside the cryostat.

of the NUCLEUS target arrays is made of Si-wafers read out by W-TES providing a 4π low-threshold inner veto to reject surface backgrounds and holder-related events. The target arrays inside the inner veto are then enclosed by cryogenic Ge detectors to reject external gamma and neutron backgrounds. The Ge veto will feature a charge read-out due to the much faster response with respect to phonon read-out.

Two $(20\times20\times5)\,mm^3$ crystals of $CaWO_4$ and Al_2O_3 have been produced and equipped with nine W-TES in spring 2021, see Figure 2. After careful testing and characterization of the TES, each crystal will be cut into nine individual $(5\,mm)^3$ NUCLEUS target detectors. A silicon mock-up of the detector module with nine Si crystals has been used for mechanical and thermal tests, see Figure 3. The Si detector dummies are held in-between a rigid 0.45 mm thick and a flexible 0.25 mm thick Si wafer. To keep the contact area between target crystals and support structure at a minimum and, thus, avoid signal phonons to escape detection in the W-TES, the contact between wafer and detector is realized by Si pyramids with a height of 0.2 mm. The Si holding plates carry all electrical and thermal connections needed for the operation of the detectors and inner veto. The contact between the non-instrumented plates and the inner veto is realized by 1 mm thick Al_2O_3 balls. In a next step, the bottom wafer will be replaced by a Si beaker for a full inner veto coverage of the target detectors. Prototype tests of the outer Ge veto with charge read-out are on-going, see Ref. [13].

3. The NUCLEUS experiment at the Chooz nuclear power plant

The NUCLEUS experiment will be located inside the Chooz reactor complex in France. We established a $24\,m^2$ room in the basement of an administrative building as the new experimental site for the NUCLEUS experiment which we named the Very-Near-Site (VNS) [12]. With a baseline of 72 m and 102 m to the two $4.25\,GW_{th}$ power reactors, we expect a high average flux

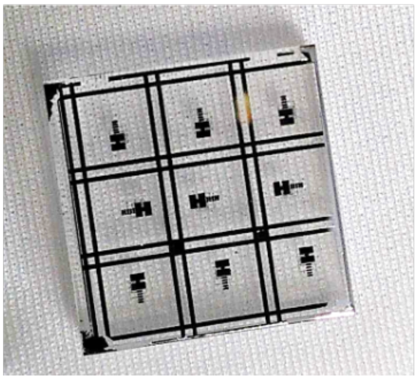

Figure 2. $(20\times20\times5)\,\mathrm{mm}^3$ Al_2O_3 crystal equipped with W-TES before cutting.

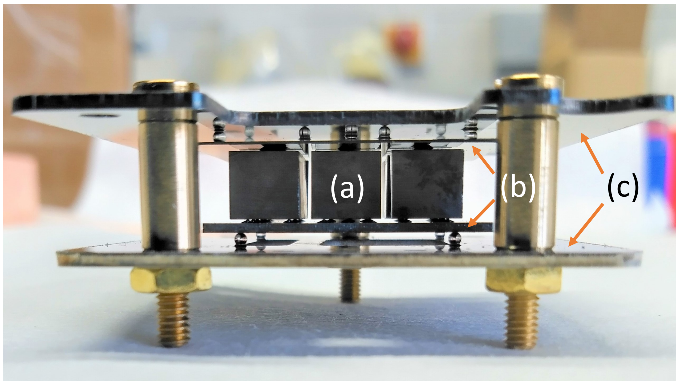

Figure 3. Si mock-up of the inner detector module: nine Si crystals (a) are mounted inside the inner veto Si wafers (b). The holding plates (c) carry the electrical and thermal connections.

of $1.7\times10^{12}\,\bar{\nu}_e/(\mathrm{s{\cdot}cm^2})$. At such distances to the reactor cores, we do not expect any reactor-correlated background. With an overburden of only 3 m.w.e. the VNS provides only limited shielding against ambient backgrounds and, thus, a careful design of the NUCLEUS shielding is needed in order to achieve the background goal of 100 counts/(keV·kg·day).

Figure 1 shows the current design of the NUCLEUS experiment. The cryogenic detectors are operated inside a dilution refrigerator. The bottom part containing the target crystals is centered inside a compact, $\mathcal{O}(1\,\mathrm{m}^3)$, passive shielding which consists of borated polyethylene (PE) and lead. The latter shields external gamma-rays, while the inner PE layer moderates and captures neutrons. The massive shielding is placed on a movable structure to access the cryostat and the inner detectors. The passive shielding is complemented with two disc-shaped shieldings inside the cryostat made of PE and Pb, respectively.

The NUCLEUS setup is completed with an active muon veto as the outermost shielding layer. We aim at a muon identification efficiency of $>99\%$. Therefore, extensive R&D work has been conducted to develop compact and efficient muon veto panels based on plastic scintillators equipped with wavelength shifting (WLS) fibers and SiPM read-out. To close the hole in the muon veto where the cryostat enters the shielding, a cryogenic muon veto operated inside the cryostat is being developed. A disc-shaped plastic scintillator is installed at the same height as the room-temperature muon veto and operated at a temperature of 800 mK. WLS fibers guide the scintillation light towards a SiPM module which is installed at the 300 K plate of the cryostat. In first prototype measurements, we could proof the applicability of this detector concept inside a running dilution refrigerator [14].

4. First estimate of the NUCLEUS background

To asses the expected background rate in the target detectors inside the full NUCLEUS shielding, we performed an extensive GEANT4 Monte Carlo simulation campaign [15]. The full NUCLEUS setup has been implemented into the simulation, including anti-coincidence cuts: for the muon veto an energy threshold of 5 MeV was applied, for the Ge outer veto 1 keV and the inner veto 30 eV. In addition, an anti-coincidence cut among the target detectors with a threshold of 10 eV was applied. Atmospheric muons have been simulated according to Ref. [16] and their secondaries dominate the estimated background in the ROI, ranging from 10-100 eV. Furthermore, ambient γ-rays have been simulated according to dedicated measurements performed at the VNS. Assuming a conservative activity of 1 kBq/kg of ^{210}Pb in the lead shielding, a small contribution of γ-background originating in the heavy shielding is expected. Overall, the estimated background is below 100 counts/(keV·kg·days), and the overall rate in the ROI is expected to be dominated by CEνNS on $CaWO_4$.

The performed MC simulations suggest that the NUCLEUS shielding efficiently mitigates the known background sources. However, many rare event search experiments observe an excess in the event rate in the few 100 eV region and below [17]. These events have a particle signature and presumably originate from different components, e.g. secondaries of atmospheric muons or holder related events. In the NUCLEUS experiment, such backgrounds are addressed by the efficient muon veto and the inner veto. In addition to mitigating this background, the different veto systems of NUCLEUS will allow to investigate these backgrounds in great detail.

5. Conclusion and outlook

The NUCLEUS experiment aims to measure CEνNS of reactor anti-neutrinos using gram-scale cryogenic detectors with an energy threshold of $\leq$20 eV_{nr}. The technical design of the experiment has been finished. Active as well as passive shieldings in and outside the cryostat enclose the target detectors by nearly 4π. Dedicated MC simulations suggest a background index of $<$ 100 counts/(keV·kg·days), thus meeting the NUCLEUS design goals.

Beginning of 2022, we will start to assemble the full NUCLEUS setup in the shallow underground lab at the Technical University of Munich. Given the limited access to the VNS, the goal is a full commissioning of NUCLEUS before its installation at the Chooz nuclear power plant. This phase includes the test and performance of the individual detector systems, an extensive calibration campaign, as well as a profound background measurement. As NUCLEUS combines very low threshold detectors with a unique system of complementary veto detectors, such a background measurement may shed light on the low energy excess observed in many Dark Matter and CEνNS experiments.

The start of the physics data taking with nine $CaWO_4$ and nine Al_2O_3 detectors is planned for 2023. This first phase, NUCLEUS-10g, will eventually be limited by statistics. In a second phase, NUCLEUS-1kg, we target to overcome this limitation by deploying a target mass of 1 kg, aiming for a precision measurement of the CEνNS cross-section at a level of 1%.

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